

# Nuclear Energy

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# Outline

- Future Energy Needs and Resources
- Nuclear Power – An Established and Improving Technology
- Nuclear is Economically Competitive and Reliable
- Nuclear Reduces Greenhouse Gas Emission
- Technical Challenges
- Fusion – Nuclear Energy of the Future
- Summary and Conclusions
- Nuclear Energy at Georgia Tech

# World Electricity Needs

(Annual Fuel Consumption<sup>a</sup>, Units  $10^{21}$  J/yr)

|   |  | 2000             | 2050                          |
|---|--|------------------|-------------------------------|
| Developed Nations <sup>b</sup><br>(USA) |  | 0.089<br>(0.039) | 0.171 <sup>c</sup><br>(0.090) |
| Former Soviet Union                     |  | 0.013            | 0.017                         |
| Developing Nations                      |  | 0.046            | 0.230 <sup>d</sup>            |
|   |  |                  |                               |
| World                                   |  | 0.147            | 0.418                         |

Source: MIT study of Future of Nuclear Power

# Major Energy Resources

(Proven Reserves<sup>a</sup>, Units  $10^{21}$  Joules)

| Region     | Coal <sup>a</sup> | Oil <sup>a</sup> | Nat. Gas <sup>a</sup> | Uranium LWR OTC <sup>a,b</sup> | Uranium U <sup>238</sup> Conv. <sup>c</sup> | Thorium <sup>d,e</sup> Th <sup>232</sup> Conv | Lithium D-T Fusion    |
|------------|-------------------|------------------|-----------------------|--------------------------------|---|---|-----------------------|
| Africa     | 1.6               | 0.4              | 0.4                   | 0.3                            | 34  |   |                       |
| N America  | 7.6               | 0.4              | 0.3                   | 0.4                            | 38  |   | 167 <sup>f,g,h</sup>  |
| S. America | 0.6               | 0.6              | 0.2                   | 0.1                            | 9   |   |                       |
| Asia       | 7.4               | 0.3              | 0.6                   | 0.4                            | 45  |   |                       |
| Europe     | 9.2               | 0.4              | 1.9                   | 0.2                            | 17  |   |                       |
| Mideast    | 0.1               | 3.9              | 1.9                   | 0.0                            | 0   |   |                       |
| Oceania    | 2.4               | 0.0              | 0.1                   | 0.4                            | 37  |   |                       |
| World      | 28.8              | 6.0              | 5.5                   | 1.8                            | 179   | 202   | 2640 <sup>f,g,h</sup> |

Source: World Energy Institute, 1999

a-h See appendix B

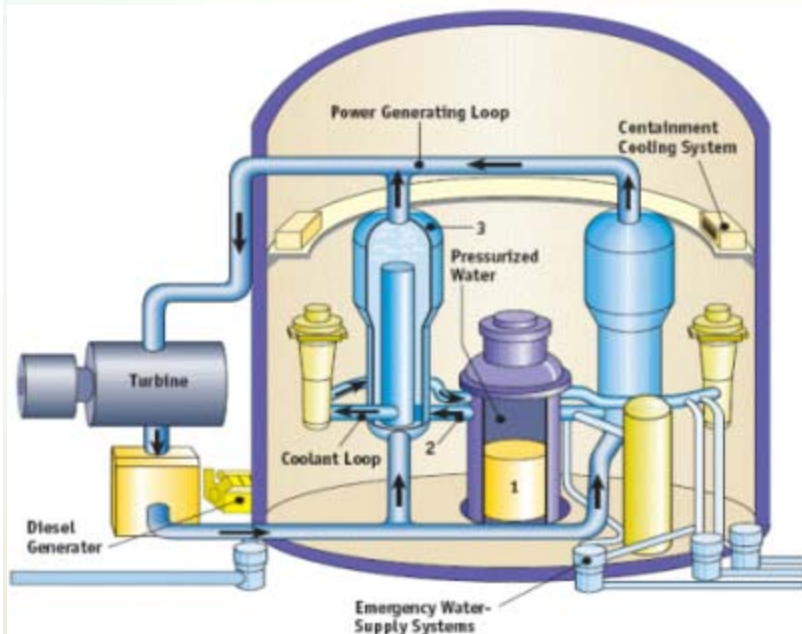
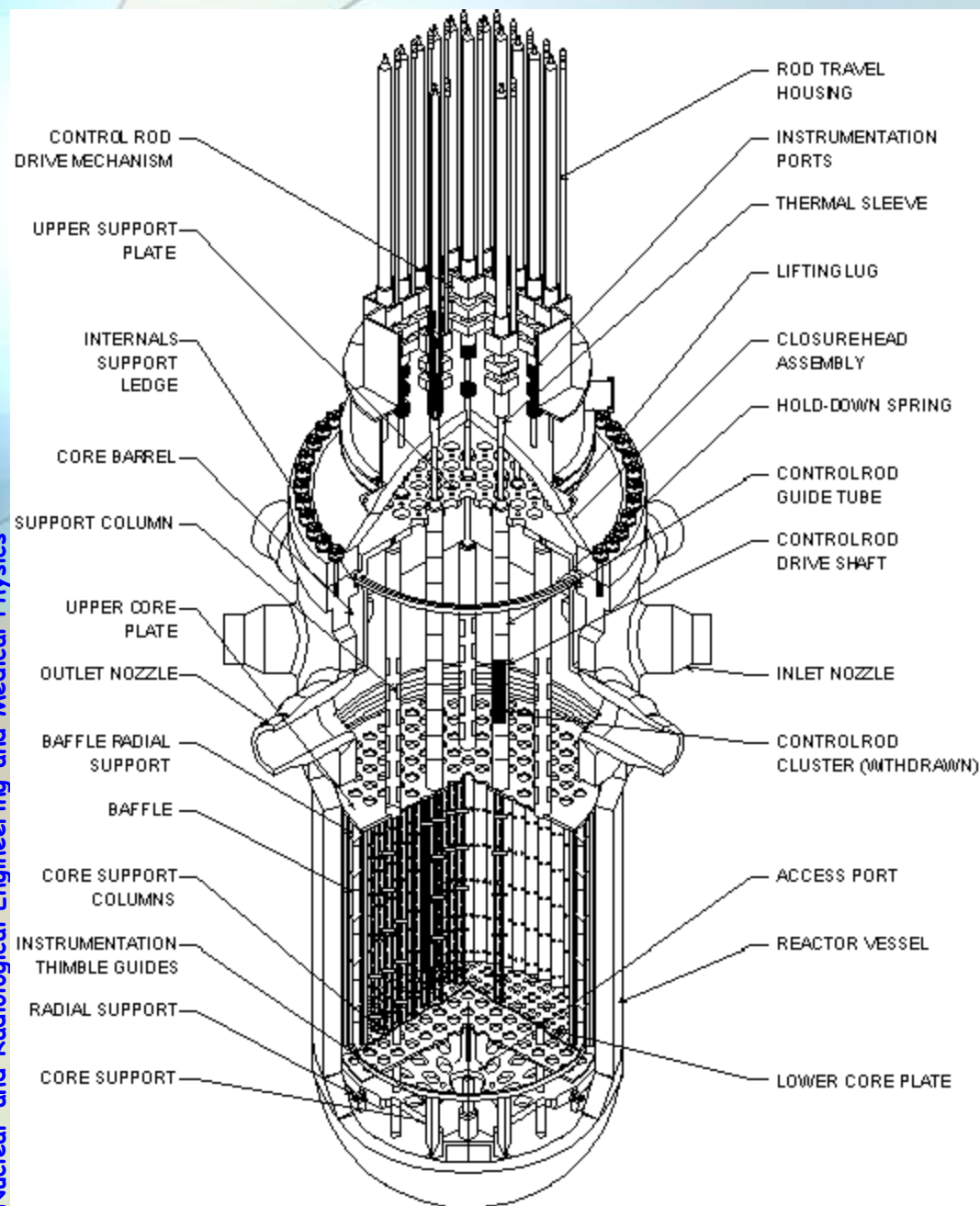
# Nuclear Reactors

- Neutron chain reaction
- Nuclear energy from fission of uranium
- Nuclear to heat to electricity

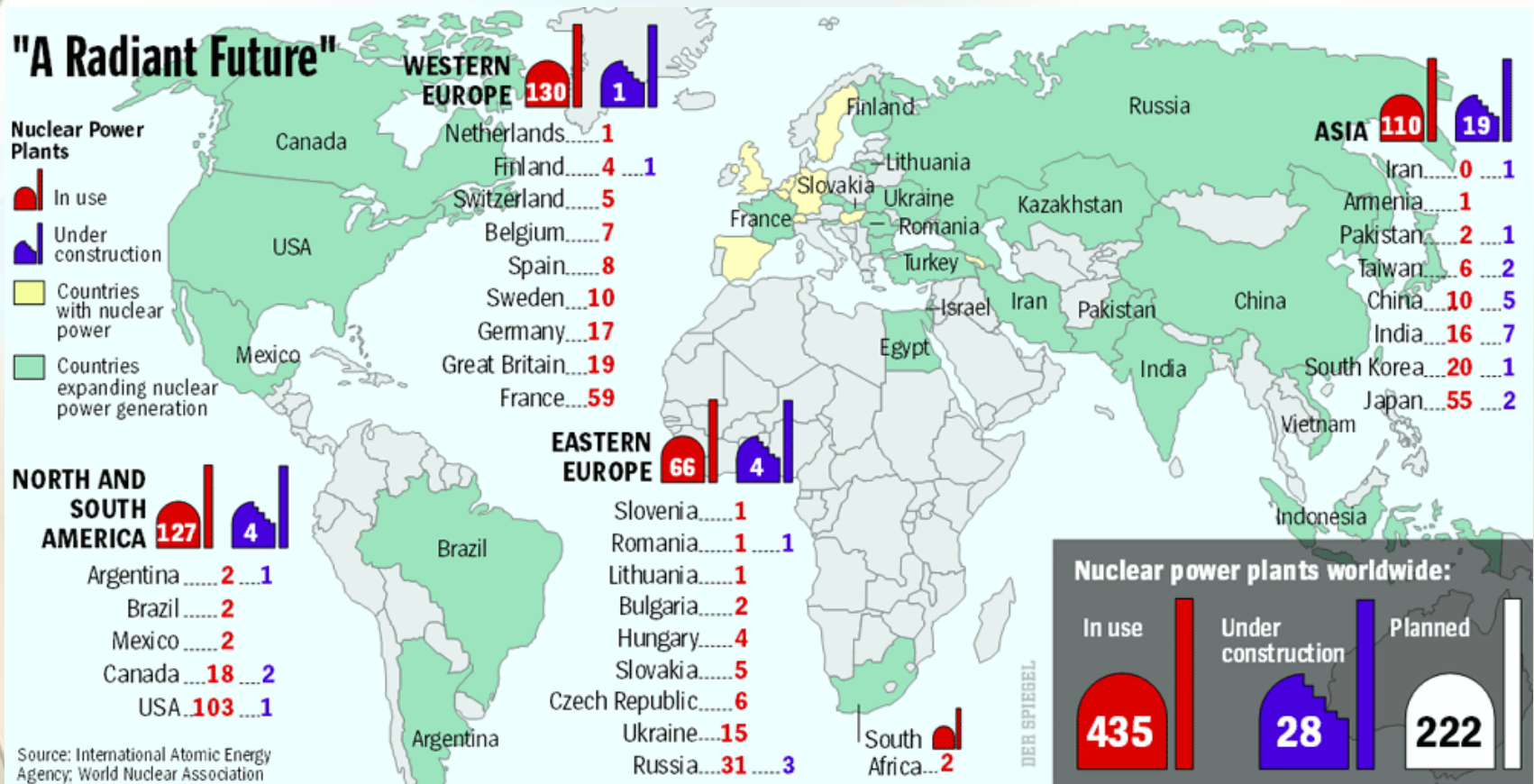
## Predominant Commercial Nuclear Reactors

- PWR – Pressurized Water Reactor
- BWR – Boiling Water Reactor
- Others—Heavy Water Reactor, Gas Cooled Reactor, etc.

# PWR



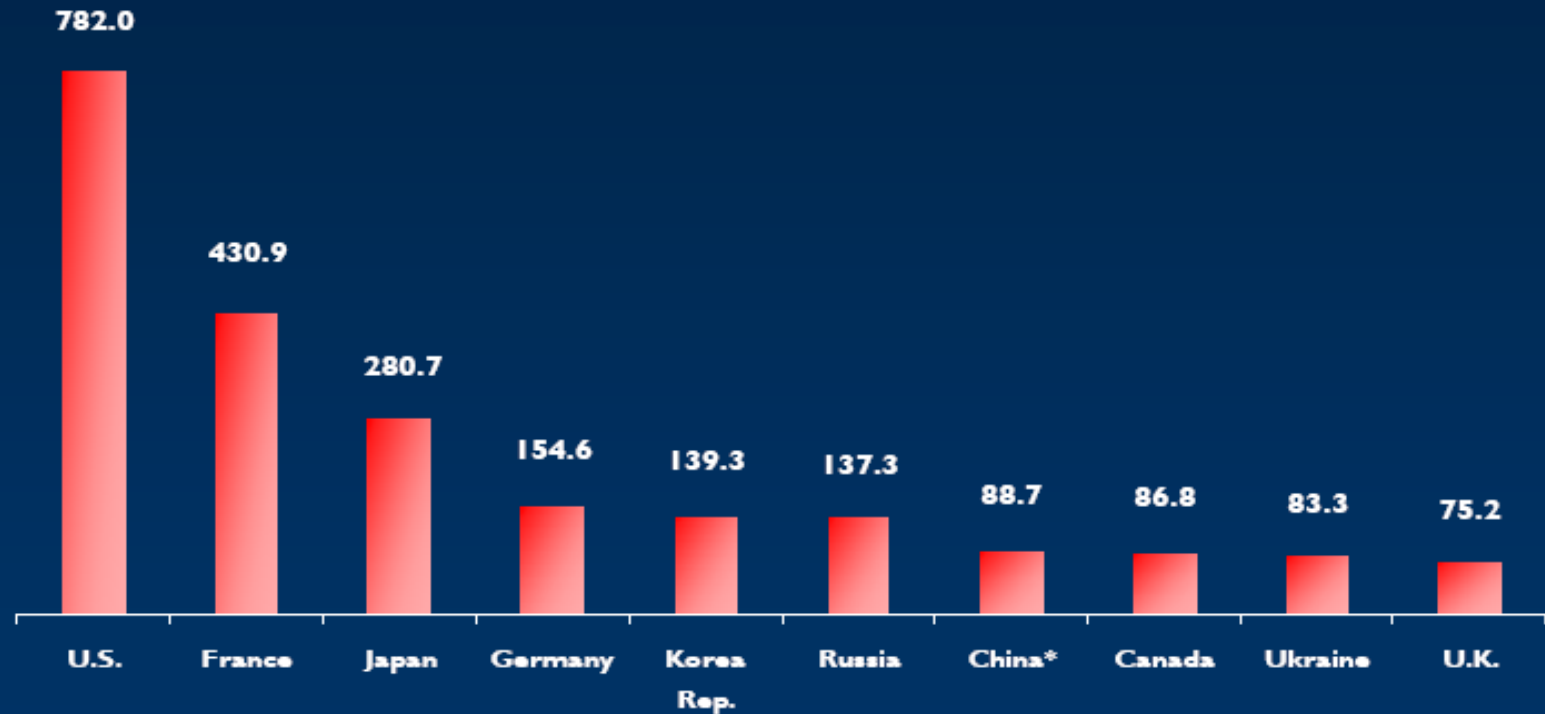
# Nuclear Power Provides 367 GWe (16%) of the World's Electricity (France 79%, USA 19%)



<http://www.spiegel.de/international/spiegel/0,1518,460011,00.html>



# Top 10 Nuclear Generating Countries 2005 (Billion kWh)



\* Includes Taiwan, China

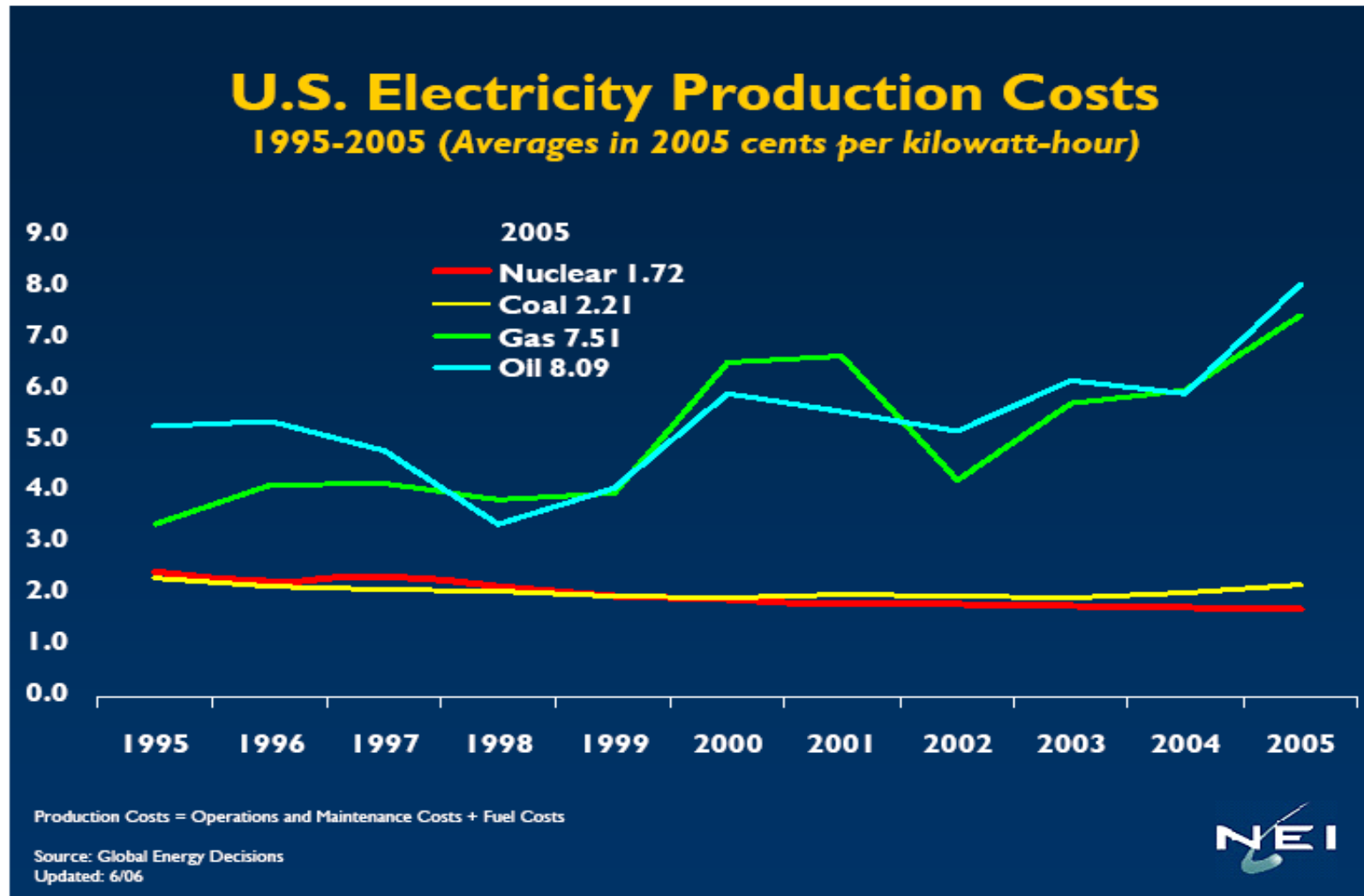
Source: International Atomic Energy Agency and Global Energy Decisions / Energy Information Administration

Updated: 11/06





# Nuclear Power is Economical



# Nuclear Plants are Reliable

## Capacity Factors – US Power Plants (2005)

| <u>Plant Type</u> | <u>Capacity Factor</u> |
|-------------------|------------------------|
| Nuclear           | 89.3                   |
| Geothermal        | 75.5                   |
| Coal              | 72.6                   |
| Natural gas       | 15.6-37.7              |
| Heavy oil turbine | 29.8                   |
| Hydro             | 29.3                   |
| Wind              | 26.8                   |
| Solar             | 18.8                   |

Capacity factor = electricity produced/electricity that could be produced

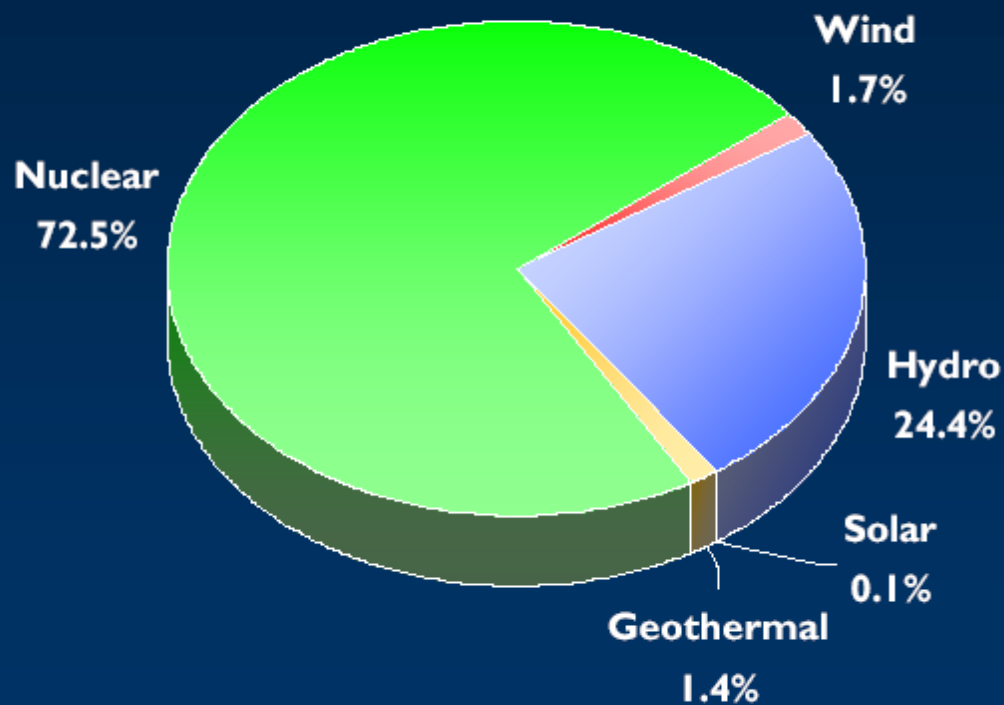
Source: NEI

# Nuclear Power Protects the Environment

- In 2005 U.S. Nuclear plants displaced fossil plants that would have emitted into the atmosphere
  - 3.32 Million Tons of  $\text{SO}_2$
  - 1.05 Million Tons of  $\text{NO}_x$ 
    - Equivalent to 41% of total passenger auto emission
  - 682 Million Metric Tons of  $\text{CO}_2$ 
    - Equivalent to 96% of total passenger auto emission
- Nuclear power plants accounted for  $>1/3$  of voluntary reductions in greenhouse gases in 2005

Source: NEI

## U.S. Sources of Emission Free Electricity 2005



Source: Global Energy Decisions / Energy Information Administration

Updated: 11/06



# Nuclear Units Under Construction Worldwide

| Country       | Units     | Total MWe     |
|---------------|-----------|---------------|
| Argentina     | 1         | 692           |
| Bulgaria      | 2         | 1,906         |
| China         | 5         | 4,220         |
| China, Taiwan | 2         | 2,600         |
| Finland       | 1         | 1,600         |
| India         | 7         | 3,112         |
| Iran          | 1         | 915           |
| Japan         | 1         | 866           |
| Pakistan      | 1         | 300           |
| Romania       | 1         | 655           |
| Russia        | 5         | 4,525         |
| S. Korea      | 1         | 960           |
| Ukraine       | 2         | 1,900         |
| <b>Total</b>  | <b>30</b> | <b>24,251</b> |

Source: International Atomic Energy Agency PRIS database

Updated: 2/07



# Advanced Reactor Status in USA

## Regulatory Design Certification

### Certified:

- **Advanced Boiling Water Reactor** design by GE Nuclear Energy (May 1997);
- **System 80+** design by Westinghouse (formerly ABB-Combustion Engineering) (May 1997);
- **AP600** design by Westinghouse (December 1999); and
- **AP1000** design by Westinghouse (February 2006)

### Active Reviews:

- **ESBWR** – GE Nuclear Energy (2005)
- **EPR** – AREVA (expected in 2007)
- **PBMR** – PBMR Pty Limited (expected in 2008)
- **US APWR** – Mitsubishi (expected in 2008)

# New Reactor Status in USA

## Utility Permit & License Preparation

- 15 Utilities are spending serious money
  - To prepare ESP and COL requests for submittal in the 2007-2009 time-frame
  - NRC approval for a COL costs \$50-\$90M (over 3-4 years)
  - At least 36 new nuclear power reactors are expected
- Reactor types to be licensed
  - 15 advanced PWRs (10 AP100, 5 EPR)
  - 7 advanced BWRs (4 ABWR, 3 ESBWR)
  - More than 17 TBD

Source: NEI

ESP: Early Site Permit

COL: Construction and Operating License



# Future Challenge for Nuclear Technology

## Closing the Nuclear Fuel Cycle

- Natural uranium
  - 0.72% fissionable  $U^{235}$  + 99.28% "Fertile"  $U^{238}$
- LWRs use uranium enriched to 3-4%  $U^{235}$
- ~ 1% of the potential energy content of uranium is recovered in the LWR "Once-Through Cycle" (OTC) in the US
  - ~ 3% is in the mining "tails"
  - ~ 2% is in the discharged "spent" fuel as  $U^{235}$  and transuranics (TRU) produced from neutron transmutation of  $U^{238}$
  - >90% is in the depleted uranium from the enrichment process and in the  $U^{238}$  in the spent fuel

# Closing the Nuclear Fuel Cycle (cont.)

- The long lived TRU (Pu, Np, Am, Cm, Cf) in spent fuel are the main reason that spent fuel must be stored in geological repositories for 100,000s of years
- These TRU are all fissionable in a fast reactor
- The >93% of uranium energy content in  $U^{238}$  can be recovered in fast reactors by
  - Neutron transmutation of  $U^{238}$  into TRU
  - Neutron fission of the TRU

# DOE Global Nuclear Energy Partnership (Deployment 2020-2030)

- Purpose
  - To develop a fuel recycling capability to enable fissioning the long-lived transuranic elements (Pu, Np, Am, Cm, Cf) in spent LWR fuel
- Components
  - Advanced burner reactor (ABR)
    - A fast reactor fueled with transuranic nuclei from LWR spent fuel
  - Consolidated fuel treatment center
    - A recycling facility that would separate the transuranics from the fission products
  - Advanced fuel cycle facility
    - For reactor fuels research
- Promise
  - Reduce high-level waste repository requirements by 10-100
    - a new Yucca Mountain every 300 years instead of every 30 years (at present nuclear power level)
  - Reduce proliferation possibilities

# International Generation-IV Studies

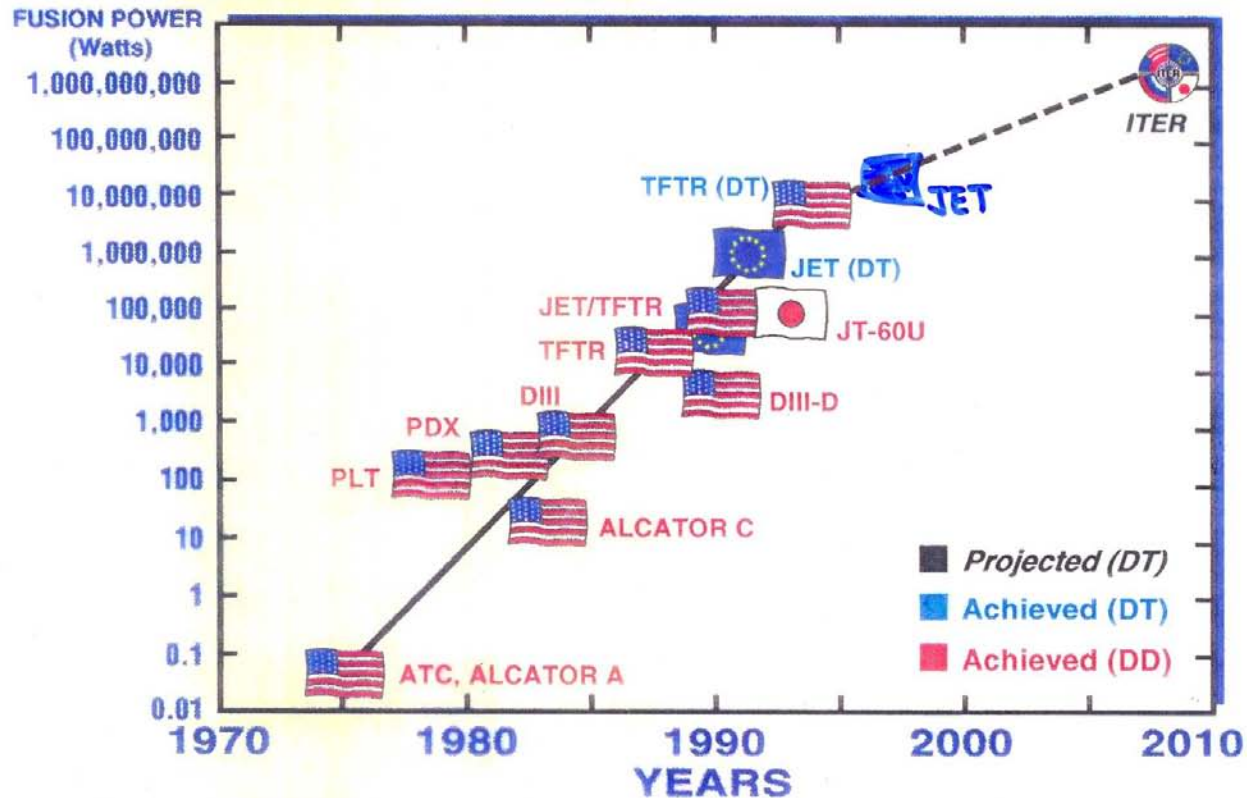
## Possible Future Reactors

- Reactor Types
  - Sodium cooled fast reactor – [closed fuel cycle](#) for uranium conversion and transuranic fission (2020)
  - Lead cooled fast reactor – [closed fuel cycle](#) for uranium conversion and transuranic fission (2025)
  - Gas-cooled fast reactor – [closed fuel cycle](#) for uranium conversion and transuranic fission (2025)
  - Very high temperature reactor – gas cooled thermal reactor for [hydrogen production](#) (2020)
  - Supercritical water reactor – high temperature thermal reactor (2025)
  - Molten salt reactor – circulating fuel epi-thermal reactor with transuranic recycle (2025)

# Fusion

- Major advances have been made in both magnetic and inertial fusion research
- The Tokamak magnetic fusion concept has reached the threshold of the physics parameter range needed for a fusion reactor
- Fusion technology that would support a fusion experimental reactor has been developed

# Progress in Magnetic Fusion Power



PLT Princeton Large Torus

PDX Princeton Divertor Experiment

JET Joint European Torus

JT-60U Japan

ITER

DIII & DIII-D

ATC & TFTR

ALCATOR A, C

International Thermonuclear Experimental Reactor

General Atomics Tokamak Experiments

Princeton Plasma Physics Laboratory

Massachusetts Institute of Technology

PPPL#93X0388

# INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

- Construction of the first fusion experimental reactor (ITER) is beginning in 2007
  - Initial operation is planned for 2016
  - ITER will
    - produce 400 MW<sub>th</sub> power
    - produce fusion power = 10 x external power to heat plasma
    - demonstrate & test reactor-relevant fusion technology
- ITER will serve as
  - A test-bed for a demonstration fusion power reactor, and
  - A prototype for a fusion neutron source to drive a sub-critical fast reactor to fission TRU fuel or convert U238 into TRU



# Summary and Conclusions

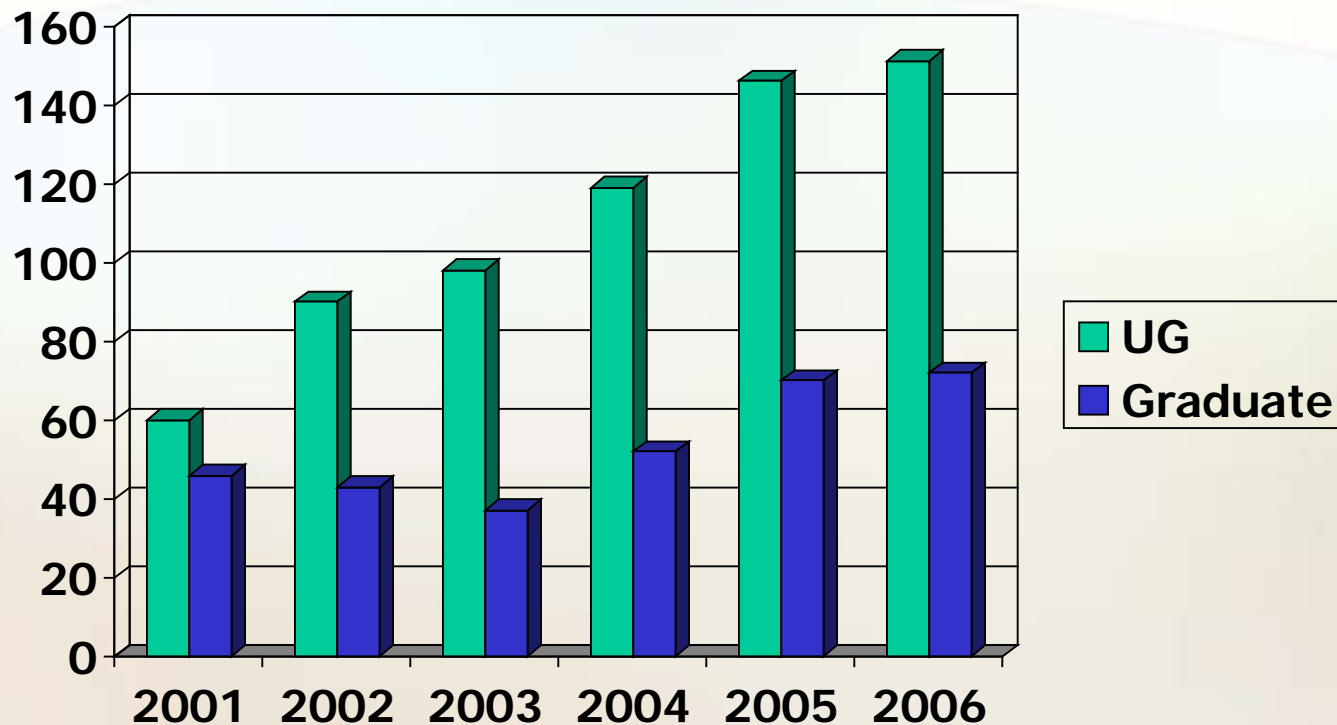
- Nuclear Energy is an established technology that is
  - Reliable
  - Economical
  - Emission-free
  - Provides 16% of the World's Electric Power
- The World's Uranium (and Thorium) resources would support a substantial expansion of the emission-free nuclear energy component of the World's growing electrical power production

# Summary and Conclusions (cont.)

- The technical challenge for Nuclear Energy is closing the Nuclear Fuel Cycle by
  - Fissioning rather than burying the TRU discharged from LWRs
  - Transmuting the fertile  $U^{238}$  into TRU that can be fissioned to recover energy
- This challenge is being addressed – GNEP, GEN-IV
- In the longer term (>2050)
  - Fusion will enable the World's Lithium resources and ultimately seawater to provide an unlimited resource for emission-free electrical power

# Student Interest in Nuclear Energy is Increasing

## NRE Enrollment Trend at Georgia Tech



# Nuclear Energy Research at Georgia Tech

- Advanced Nuclear Reactor Design
  - Generation-IV & Advanced Burner Reactor Design
  - Analyses of Closing the Nuclear Fuel Cycle
- Nuclear Reactor Core Simulation Methods
  - Improved Computational Models for Advanced water reactors, VHTRs, ABR
  - Advanced Radiation Transport Code (neutron, photon & electron transport)
- Fusion Plasma Physics and Technology
  - Plasma Theory & Exp. (D-III National Tokamak Team)
  - Conceptual Design of Neutron Sources & Reactors
- Heat Removal from Fission & Fusion Reactors
- Radiation Detection and Protection

# Questions?

# Appendix A

- a J thermal fuel consumption =  $\frac{1}{3}$  J electrical
- b > 4000 kWh per capita per year PER
- c **Population growth rat 0.1 – 1.0% per year**
- d Population growth rate 1% per year

# Appendix B

- a** Source: World Energy Institute, 1999
- b** 1 tonne U = 13,000 toe in LWR OTC @ 1% utilization =  $5.46 \times 10^{14}$  J
- c** 100% utilization via transmutation of U238 into Pu239
- d** Source: US Geological Survey Mineral Commodity Summaries, 2005
- e** 1 ton Th232 =  $2.7 \times 10^{28}$  atoms U233 on neutron capture, which yields  $8.1 \times 10^{16}$  J when fissioned
- f** Source: US Geological Survey Mineral Commodity Summaries, 2001
- g** 1 ton Li =  $7.8 \times 10^{28}$  atoms T on neutron capture, which yields  $2.2 \times 10^{17}$  J when fused with D
- h** For D-D fusion, the fuel is seawater, which is virtually an unlimited energy resource

## NOTES

1. Heavy oils and bitumen resources comparable to Mideast oil reserves, but recoverability is an issue.
2. Methane hydrates exceed conventional gas reserves, but recoverability is an issue.
3. Windpower comparable to electricity demand is technically feasible, but land use is an issue.



# Nuclear Reactors

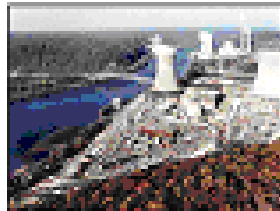
- Nuclear reactors are assemblages of fuel, coolant, structure, shielding, etc
- Controlled neutron chain reaction is maintained by fissioning heavy mass nuclei (e.g.,  $U^{235}$ )
- The thermal energy is then removed and converted to electricity or process heat
- Reactors are characterized by
  - Neutron energy distribution, e.g.,
    - Thermal
    - Fast
  - Energy distribution is mainly determined by the coolant (moderator) type, e.g.,
    - Water (thermal reactors)
    - Sodium (fast reactors)

# Nuclear Reactor Evolution

## The Evolution of Nuclear Power

### Generation I

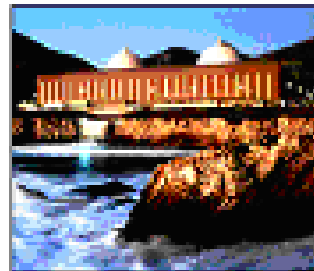
Early Prototype Reactors



- Shippingport
- Dresden, Fermi I
- Magnox

### Generation II

Commercial Power Reactors



- LWR/PWR, BWR
- CANDU
- VVER/REMK
- AGR

### Generation III

Advanced LWRs



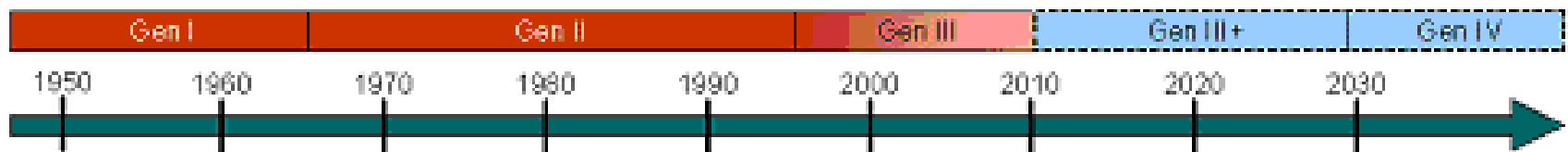
- ABWR
- System 80+
- AP600
- EPR

### Generation III+

Generation III Evolutionary Designs Offering Improved Economics

### Generation IV

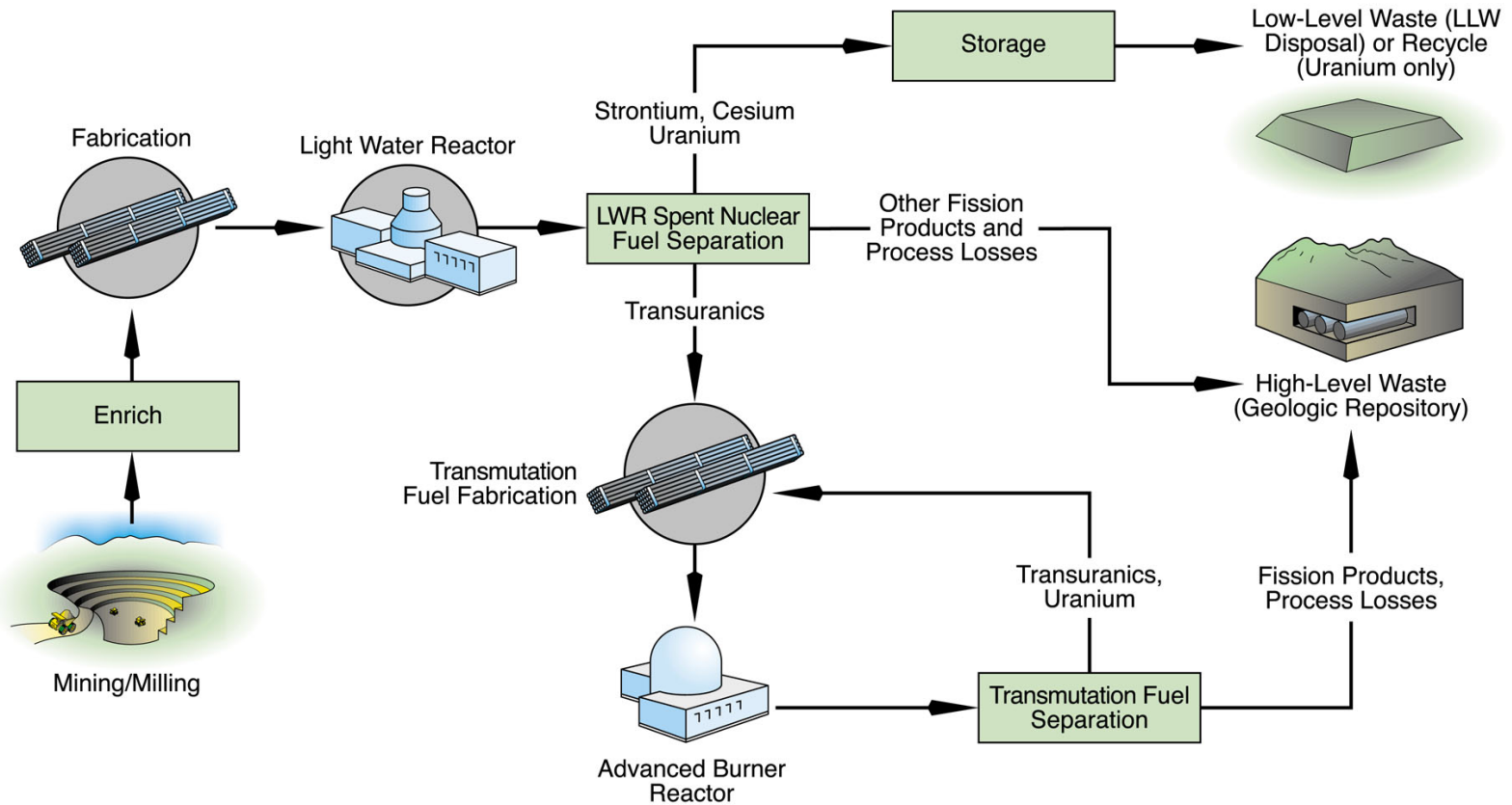
- Highly Economical
- Enhanced Safety
- Minimize Wastes
- Proliferation Resistant



# World Nuclear -- Electricity Production (Source: NEI)

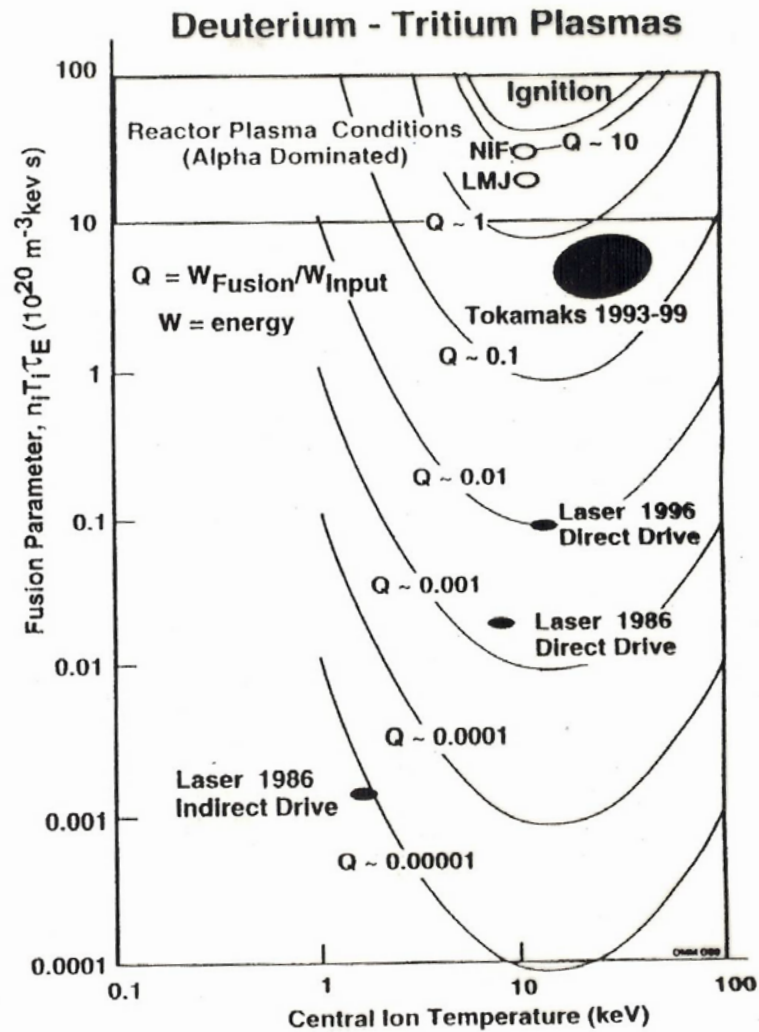
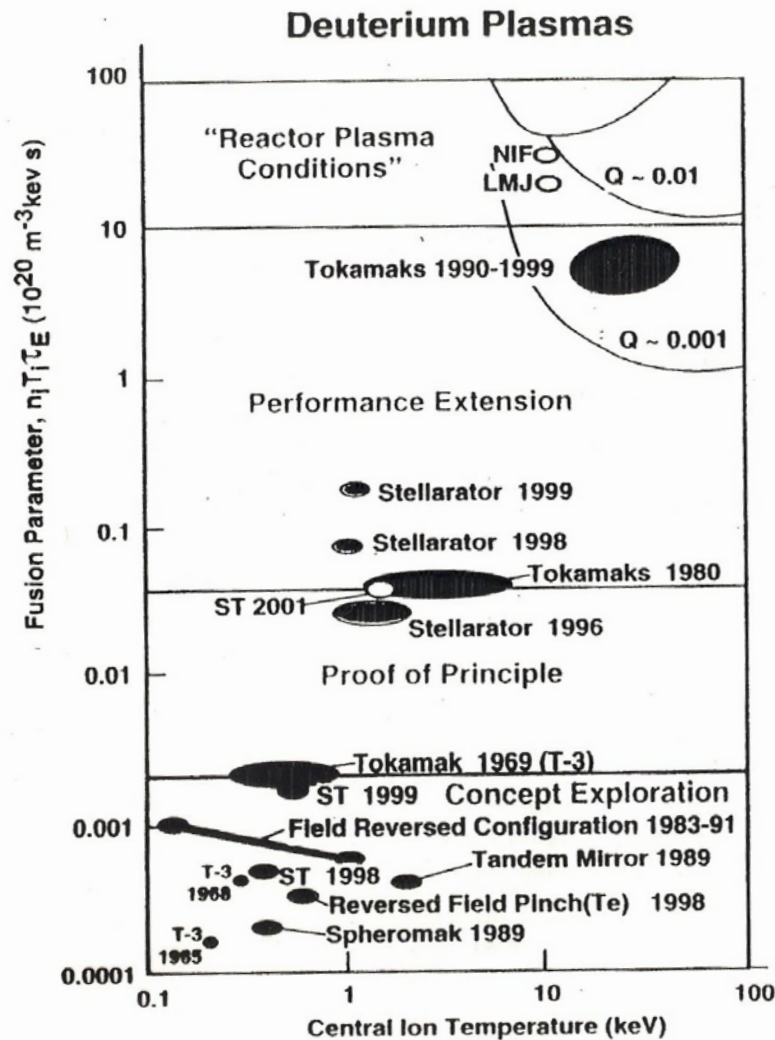
| <u>Country</u> | <u>#</u> | <u>MWe (1/07)</u> | <u>%</u> |
|----------------|----------|-------------------|----------|
| Belgium        | 7        | 5,801             | 55.6     |
| Canada         | 18       | 12,584            | 14.6     |
| China          | 16       | 12,456            | 2.0      |
| France         | 59       | 63,363            | 78.5     |
| Germany        | 17       | 20,339            | 31.0     |
| India          | 16       | 3,483             | 2.8      |
| Japan          | 55       | 47,593            | 29.3     |
| Korea          | 20       | 16,810            | 44.7     |
| Russia         | 31       | 21,743            | 15.8     |
| Spain          | 8        | 7,450             | 19.6     |
| Sweden         | 10       | 8,909             | 46.7     |
| Switzerland    | 5        | 3,220             | 32.1     |
| Ukraine        | 15       | 13,107            | 48.5     |
| U.K.           | 19       | 10,982            | 19.9     |
| U.S.           | 103      | 98,466            | 19.3     |
| Other          | 36       | 21,487            |          |
|                |          |                   |          |
| Total          | 435      | 367,793           | 16.0     |

# *GNEP Deployment System*

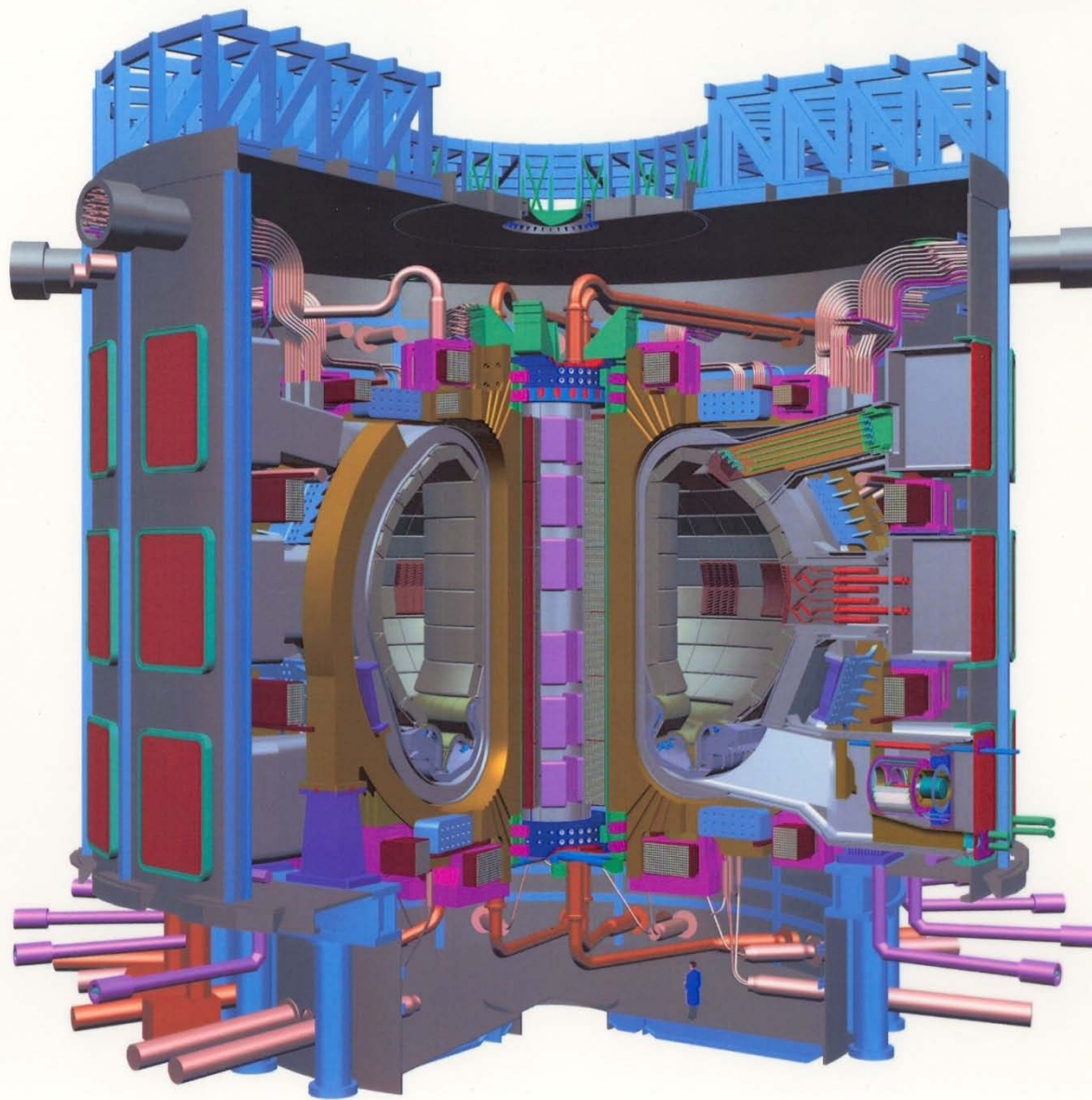


# Generation-IV Studies of Possible Future Reactors

- Purposes is to achieve
  - better uranium utilization
  - minimum nuclear waste discharge
  - enhanced safety
  - reduced cost
  - enhanced proliferation resistance
  - produce energy and/or hydrogen
- Potential deployment in 2030-2040









# Nuclear Energy Education at Georgia Tech

- Nuclear and Radiological Engineering Program offers the following degrees
  - BSNRE
  - MSNE
  - PhD
- One of the largest NE enrollments in the US